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6 ARRAYS VERSUS LENSES AS DIRECTIONAL ACOUSTIC SENSORS

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Marine Physical Laboratory
ARRAYS VERSUS LENSES AS DIRECTIONAL
ACOUSTIC SENSORS

SPECIAL REPORT
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There are two major techniques today for creating directional acoustic sensors. These are: the use of an array of point receivers, coupled into an electrical beamforming network on the one hand and the use of a refractive lens to focus the sound rays to a localized region on the other hand. The essential difference between these two methods lies in the way in which the transformation of a plane wave acoustic field into a diffraction limited region takes place. In the case of the lens, the actual acoustic field is modified locally by refraction and the transformation of the plane wave field into the diffraction limited region takes place within the acoustic field itself whereas the array samples the acoustic field without perturbing it and then electrically combines the samples to generate the transform of the plane wave acoustic samples into a diffraction limited signal.

It is interesting to look at the implications of these differences in terms of the performance of these two techniques as directional sensors. In general there is no inherent difference in resolution or in directional response pattern between the two. In both cases the transformation which is made is aperture limited and a lens of a given, physical aperture, can have the same performance as an array of the same aperture and conversely, an array of that aperture can have the performance of a lens of a comparable aperture. Thus the differences between the two techniques must lie in other areas. For example, as a transmitter, there is a gross difference in source level capability. The cavitation limit which is the usual limitation for a projector's transmitted power provides a serious limit in the case of the lens because the cavitation limit occurs at the focal point and here the limit would represent a total power that is lower than that for a full aperture transducer by the directivity index of the aperture. Thus differences in the source level of the order of 20 to 30 dB may be expected between a lens and a corresponding filled array aperture. Because of this limitation, except for rather unusual circumstances, the main interest then in the use of a lens versus an array lies in the use as a receiving rather than a projecting element.

Consider first the use of the two methods in a signal field. Since there is no inherent difference in resolution and directional response, one must look at other features. One of these is the use of it as a single beam trainable transducer. The lens must be mechanically trained, that is either the entire lens as a single receiving transducer assembly must be rotated or else the transducer assembly itself can be rotated around a lens providing there is an approximate symmetry of the lens. On the other hand, the steered acoustic transducer can be trained in electrically implemented steps which can be made arbitrarily small controlled only by the quantization imposed by the electronics. Thus the trade off in this area is a trade off between mechanical systems and electronic systems, but unless one gets into actual system details a quantitative comparison can't be made other than to say that there is probably a weight advantage for the electronic steering in contrast to the mechanical steering but that the cost advantage might be in the other direction. These generalization, however, are not ones that can be asserted with any confidence.

Another feature of the lens is that the signal pressure at the focal point is higher than the pressure that would be received by an element of an array by a factor equal to the directivity index. In the case where sensors are self-noise limited this is an advantage. Of course, in the underwater acoustic field it is usually possible to design point receiving acoustic sensors which are medium noise limited rather than self-noise limited for all bands and levels of interest, so this increase in signal strength is not a significantly important feature of the acoustic lens although it has been a major advantage for the electromagnetic Luneberg lens.

Consideration of the performance in a noise field is slightly more complicated, particularly because one must consider a number of different types of noise sources. The usual ambient noise background of the ocean, associated with distant sources can be considered in a manner similar to the signal response. Here it is strictly the directional characteristic of the sensor that counts and, since the beampattern and directional response patterns can be achieved to an equal degree in either configuration, one can assert that the ambient noise performance would show no essential difference between the two techniques.

When flow noise is considered, another situation arises. Here the problem is that the noise sources are locally distributed. They usually occur at the boundary between the water and the acoustic dome environment and so the model used is that of a set of incoherent pressure sources acting across the face of the dome. The spatial correlation distance of the source's pressure distribution on the boundary is short for the turbulent pressure field. Thus there is a gain in noise performance by placing the transducer receiving element some distance from the dome surface so that the pressure fields from the turbulent noise sources are averaged. This is the well-known windscreen effect that has been used for years in microphones to shield against turbulent wind noise. If one takes either a multi-element array aperture or a lens and places either within a given dome, the acoustic sensors themselves will, in general, be the same distance from the dome surface since the apertures are of comparable size. This should be qualified, of course, because the edges of the transducer array will be somewhat closer to the dome than will be the center. However, in like manner, sensor elements for the lens will be distributed around the periphery of the lens and some of them will be closer to the dome surface for other than bore-sight angles.

Thus, the physical sensor locations are comparable, and it turns out that the flow noise response is essentially the same for the two systems--however the mechanism by which it occurs is different. The focussing action of the lens gives a higher signal-to-noise ratio at an individual element by virtue of the directivity index which enhances the signal strength with respect to the uncorrelated noise response from the dome noise. On the other hand, for the array, the signal coherence over each of the elements is used in the electronics to enhance the signal but the flow noise components of the element outputs will be combined incoherently so that once again the directivity index at the beamformer output discriminates between the flow noise and signal. It provides essentially the same value of directivity index as the focussing directivity index of the lens.

It is easy to see that the structure-borne noise follows the same general pattern. Although the signal strength is higher in the sensor receivers for the lens, the incoherent summation of the noise from a large number of sensors does not take place because each direction is associated with only one transducer on the lens. Thus any difference between the performance of the two lies in the details of the transducer mounts and the vibration sensitivity of the individual sensors rather than in the inherent characteristics of the spatial processing used.

Turning now to the multi-beam passive sonar embodiment of a directional sensor system we find that the use of a lens in this context raises some serious practical problems which have to be overcome. First of all there is the inherent problem of beam-to-beam balance in any multi-beam system. In the multiple array processing using digital processing, and in particular the polarity sampling or DIMUS concept, the normalization or reproducibility of beam levels is achieved inherently in the processing, and it is possible to work to extremely small differences between power levels on adjacent beams. In the lens configuration, however, one must rely on the match of the analog response of the sensor elements themselves, and the level of matching required extends well beyond the normal transducer tolerances one gets in production units so special care must be taken in this case. As an illustration of this, it is my recollection that, in the Fogcutter application of a lens as a passive detector, the actual measured performance of the system was some 20 to 30 dB poorer than one would predict on the basis of the background noise and signal strengths expected. This was directly attributed to the problem of beam-to-beam balance. One solution to the beam balance problem is the use of "split away" or multiplicative processing. This increases the complexity of the electronics, trading off cost against performance.

Another problem in the multi-beam application is the shadowing of the lens by the receiver elements. Once one covers an aperture that exceeds about ±45°, the sensors for some of the peripheral beams will be in the forward lens aperture for some other extreme beams and there will be a shadowing effect and a consequent degradation of the beam pattern of the lens for those angles. If one is concerned about a nearly full 360° aperture this shadowing becomes a very serious practical problem and the array gains and noise performance for a limited aperture system may not at all be representative of the filled sensor pattern on the lens.

There is a further complication in that in some lens systems a simple point sensor does not achieve the beam pattern characteristics desired for the lens and it becomes necessary to introduce directional cardiod sensors at the focus. As an example, it has been expedient to use clusters of these for each focal point so that one uses a sub-array for each focal direction. This, of course, complicates the simplicity of the lens transform mechanism and increases the number of electrical interconnections associated with the beamforming process for the lens.

Also it should be recognized that the one significant difference between the lens and the array -- that of the actual signal pressure gain at the focal point -- is offset by the requirement of cardiod sensors, which, in general, for a broadband operation have a significantly lower acoustic sensitivity and correspondingly are more subject to self-noise limitation. If, instead of gradient type sensors, one uses pistons which have a physical aperture for directionality, then the shadowing effect becomes intolerable because the entire aperture has to be essentially blanketed with shoulder-to-shoulder transducers and the forward section of the lens would be virtually completely blocked by the receiving transducers.

The choice between the use of a lens or of an array as a passive sonar receiving sensor then obviously resolves down to a cost/weight comparison. The other intrinsic differences are either small or offsetting in terms of the inherent performance advantage of the two techniques. Some of these "non-performance" considerations are:

1) The fouling problems for Luneberg lens systems used in a seawater flooded dome where biological growth can occur can be a serious problem.

2) In the case of a liquid filled lens there is a significant weight associated with the liquid in the lens. This may well be considered deadweight in a submarine application because the weight of the liquid would not be available as blowable ballast for surface mode of operation and thus would represent a significant additional ballasting requirement for surface operation.

3) If one looks at the number of transducer elements involved it is apparent that, for a multiple beam system there is really no fundamental difference in the number. The number of elements in an array is, in general, equal to the directivity factor, and this in turn is also the ratio of the angular aperture divided by the number of beams. For the lens the number of sensors is equal to the number of beams to be formed and actually could be higher in the case where sub-arrays of sensors are used. Thus, the numbers of elements for either the lens or the array are essentially equal. The trade off comes in trading off the cost of the liquid lens which for large sizes could be a significant mechanical system against the electronics associated with the multiple element combination in a beamformer configuration.

Evaluation of cost/weight advantages would obviously have to be done on the basis of two optimized designs -- one for the lens and the other for the array in a realistic total system concept where accurate costing versus performance can be carried out with confidence.

In the face of all these considerations one cannot do much more than make a general statement that there is probably an advantage for a lens in terms of cost and weight for a narrow sector tracking or sweep search mode of operation but, in general, there would not be an advantage with a wide aperture multi-beam passive detection mode of operation. It should also be pointed out that the array technology, that is, the technology of acoustic transducers and the electronics, particularly digital electronics, is more advanced as a result of the development that has been done in other fields, than is either the fluid or compliant tube lens technology which is more limited and restricted to the underwater acoustics field and correspondingly is a somewhat higher risk. By way of illustration one could say that it probably would be more difficult for an unimaginative designer to louse up an electronically steered array system than it would be for an unimaginative designer to blow a lens system design.

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